# Oxygen Isotopes in Refractory Inclusions from the Adelaide Carbonaceous Chondrite

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**OXYGEN ISOTOPES IN REFRACTORY INCLUSIONS FROM THE ADELAIDE CARBONACEOUS CHONDRITE.** G. R.. Huss[1,2], I. D. Hutcheon[3], A. N. Krot[4] and S. Tachibana[1], [1]Department. of Geological Sciences and [2]Center for Meteorite Studies, Arizona State University., Tempe, AZ 85287 (gary.huss@asu.edu). [3]Lawrence Livermore National Laboratory, Livermore, CA 94551; [4]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, HI 96822.

**Introduction:** Adelaide is an anomalous carbonaceous chondrite with a CV-like bulk O composition ($\Delta^{17}O$ = -3.6 ‰), abundant small chondrules, and an anhydrous low-FeO matrix [1,2]. Its bulk composition, which is highly depleted in volatiles [3], and the H, N, and C isotopic compositions and abundances [4] suggest that its nearest relatives are Bench Crater and Kakangari [5]. Refractory inclusions comprise several percent of Adelaide and include melilite-rich CAIs, often containing spinel and hibonite, hibonite-rich CAIs, sometimes containing corundum, grossite-rich CAIs, and anorthite-spinel inclusions, among other types. The mineralogy and Al-Mg isotopic data [2, unpublished] indicate that Adelaide CAIs were largely unaffected by the metasomatism that altered CAIs in CV and CO chondrites, the aqueous alteration that was pervasive in CM chondrites, or thermal metamorphism. Adelaide CAIs may thus be among the best preserved CAIs available for study. As part of a broader study of refractory objects in Adelaide, we have made O-isotope measurements on 12 objects.

**Experimental:** Five thin sections were studied by petrographic microscope, then X-ray mapped in Ca, Al, and Mg K$\alpha$ to identify all refractory objects. A subset, selected to include most important types, was measured for O isotopes with the ASU Cameca ims-6f ion microprobe. The 0.5nA Cs$^+$ primary ion beam was focused in aperture-illumination mode to produce a ~20 μm spot. The secondary column was operated at -9 kV with a mass resolving power of 5500 and a 75 eV energy window. The normal-incidence electron flood gun was used for charge compensation. Negative $^{16}O$ ions were measured on the Faraday cup and $^{17,18}O^-$ were measured on the electron multiplier. Crestmore olivine ($Fa_{0.7}$) was the standard. Although there is a significant matrix effect associated with Fe abundance, there does not seem to be significant matrix effect for Fe-free minerals.
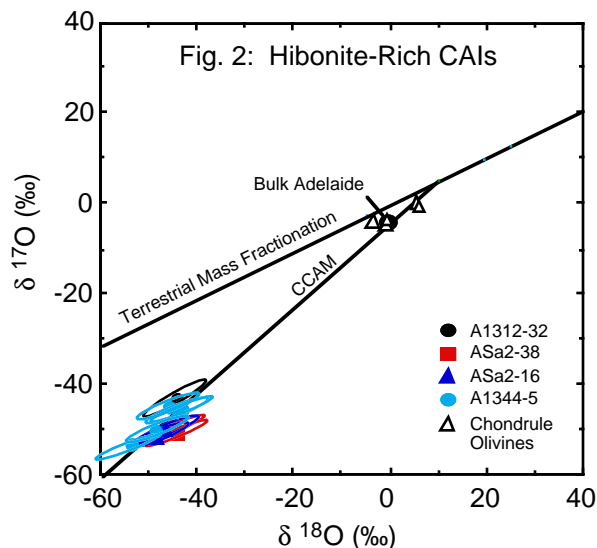
**Results:** Two melilite-rich inclusions were measured. ASa2-2 is a compact Type A inclusion composed of spinel with hibonite laths and melilite and rimmed by anorthite and pyroxene. It shows an undisturbed isochron with $(^{26}Al/^{27}Al)_0$ = 4.8×10$^{-5}$. Melilite and spinel have the same $^{16}O$-rich composition ($\Delta^{17}O$ ≈ -22 ‰); the rim is less $^{16}O$-rich ($\Delta^{17}O$ ≈ -17 ‰) (Fig. 1). A1344-70 is a compact Type A inclusion rimmed by spinel, anorthite, and pyroxene. It has been heavily weathered on earth, with much of the melilite

replaced by a hydrated, Ca-poor aluminosilicate. Spinel in A1344-70 is $^{16}O$-rich ($\Delta^{17}O$ ≈ -25 ‰), while melilite exhibits a range of compositions along the CCAM line (Fig. 1). Pyroxene in the rim is slightly less $^{16}O$-rich than spinel ($\Delta^{17}O$ ≈ -22 ‰).



Fig. 1: Melilite-Rich CAIs
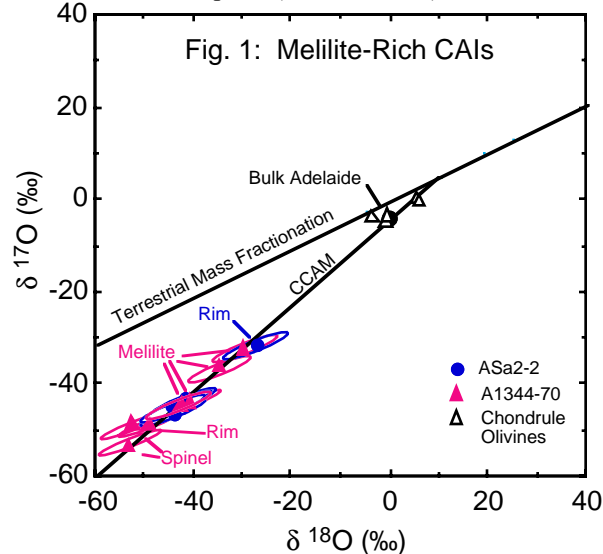
Four hibonite-rich inclusions were measured. A1344-5 (HM-1 in [2]) is a compact inclusion of tightly intergrown hibonite (75%) and gehlenitic melilite (25%) with accessory perovskite. No spinel is present. A1344-5 displays an undisturbed Al-Mg isochron with with $(^{26}Al/^{27}Al)_0$ = 4.4×10$^{-5}$ [2]. Hibonite and melilite are both $^{16}O$-rich (Fig. 2). There is a small range in $\Delta^{17}O$ of the hibonite (-26 ‰ to –22 ‰) with melilite falling at the $^{16}O$-poor end of this range. A1312-32 and ASa2-16 consist of hibonite laths arranged in a radial pattern. Hibonite in A1213-32 contains tiny inclusions of corundum [6]. The interstitial space is filled with weathering products, although in some similar inclusions, melilite is present between the laths. ASa2-16 shows no evidence of $^{26}Al$. The hibonite in both inclusions is very $^{16}O$-rich with $\Delta^{17}O$ ≈ -20 ‰ and –26 ‰, respectively (Fig. 2). Inclusion ASa2-38 consists of two rounded hibonite nodules enclosing minor perovskite and surrounded by layers of weathering products (formerly melilite?) and pyroxene. ASa2-38 shows no evidence of $^{26}Al$, but the hibonite is very $^{16}O$-rich ($\Delta^{17}O$ ≈ -27 ‰) (Fig. 2).

Two spinel-anorthite-pyroxene inclusions studied, ASa2-17 and A1312-48a, consist of spinel grains enclosed in anorthite and surrounded by pyroxene. Spinel

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Fig. 2:  Hibonite-Rich CAIs

δ $^{17}$O (‰) vs δ $^{18}$O (‰)

Bulk Adelaide
Terrestrial Mass Fractionation
CCAM

Legend:
● A1312-32
■ ASa2-38
▲ ASa2-16
● A1344-5
△ Chondrule Olivines

is relatively $^{16}$O-rich in both inclusions ($\Delta^{17}$O ≈ -16 ‰ and -20 ‰, respectively), but less $^{16}$O-rich than spinel in melilite-rich and hibonite-rich CAIs.  Anorthite in ASa2-17 is relatively $^{16}$O-poor ($\Delta^{17}$O ≈ -5 ‰ to -9 ‰), like chondrule olivines, while anorthite in A1312-48a shows a range of more $^{16}$O-rich compositions ($\Delta^{17}$O ≈ -12 ‰ to -21 ‰).  Pyroxene in A1312-48a is slightly more $^{16}$O-rich ($\Delta^{17}$O ≈ -22 ‰) than the spinel.

ASa3-11 is an igneous fragment consisting of laths of plagioclase with interstitial pyroxene.  This inclusion shows a hint of $^{26}$Al with ($^{26}$Al/$^{27}$Al)$_0$ = 4.6×10$^{-6}$. Plagioclase and pyroxene have $\Delta^{17}$O ≈ -4.5 ‰, similar to the Adelaide whole-rock value.

Three objects have relict refractory components within less refractory material.  ASa3-18 is an igneous inclusion containing a single large hibonite grain surrounded by plagioclase laths and interstitial melilite. There is no evidence of $^{26}$Al.  Hibonite in ASa3-18 is extremely $^{16}$O-rich ($\Delta^{17}$O ≈ -26 ‰).  Anorthite ranges from $\Delta^{17}$O ≈ -22 ‰ to -27 ‰, while melilite ranges from $\Delta^{17}$O ≈ -8 ‰ to –14 ‰.  The terrestrial-alteration phase replacing melilite has $\Delta^{17}$O ≈ -2 ‰.  1312-38 is an olivine-pyroxene-plagioclase chondrule containing an ovoid region of anorthite, pyroxene, spinel, and minor olivine.  Spinel and plagioclase in the interior object have $\Delta^{17}$O ≈ -16 ‰ to -7 ‰, while surrounding olivine has $\Delta^{17}$O ≈ -4.5 ‰.  ASa3-9d consists of a hibonite-melilite-spinel CAI surrounded by a plagioclase rim enclosed within a porphyritic olivine-pyroxene chondrule with plagioclase mesostasis [7].  Hibonite and spinel in the CAI give an apparent $^{26}$Al isochron with ($^{26}$Al/$^{27}$Al)$_0$ = 3.7×10$^{-5}$ but melilite and surrounding plagioclase show no evidence of $^{26}$Al.  Hibonite+melilite (grains too small to measure individually) gives $\Delta^{17}$O ≈ -23 ‰, surrouding olivine gives $\Delta^{17}$O ≈ -8 ‰, and plagioclase gives $\Delta^{17}$O ≈ -7 ‰ to -12 ‰.

**Discussion:**  Much of the variation in the O composition of melilite may be due to terrestrial weathering.  Several CAIs, particularly A1344-70 and ASa3-18, have had much of the melilite replaced by a hydrous, Ca-poor aluminosilicate during terrestrial weathering.  Similar material is present in CAIs from other carbonaceous chondrite finds (e.g., Leoville). Both A1344-70 and ASa3-18 have variable O compositions for melilite.  Melilites with $^{16}$O-poor compositions had higher $^{16}$OH$^-$ peaks than other minerals and the hydride tended to anti-correlate with $^{16}$O-richness. This suggests that melilite is being converted to hydrous aluminosilicate and that the variations in melilite O composition are due to addition of terrestrial water.

If the variations in melilite composition are terrestrial in origin, then melilite-rich and hibonite-rich CAIs were probably all uniformly $^{16}$O-rich prior to weathering, with a relatively small spread in $\Delta^{17}$O (-20 ‰ to -27 ‰).  There is no correlation between O and $^{26}$Al. Some inclusions are $^{16}$O-rich and formed with $^{26}$Al (A1344-5) while others are $^{16}$O-rich but apparently had no $^{26}$Al (ASa2-16).  The O varations in the hibonite-rich CAI, A1344-5, may reflect evolution of the bulk O composition while the CAI crystallized.  Rim pyroxenes tend to be less $^{16}$O-rich than the inclusions they rim, suggesting formation from a different O reservoir.

Less-refractory objects and objects that appear to contain relict CAI material are less $^{16}$O-rich than CAIs and many show a range of O compositions.  ASa3-11, the igneous-looking fragment consisting of plagioclase and pyroxene is the only one of these objects that appears to have equilibrated O.  The relic CAI in ASa3-9d probably started out with the same O and $^{26}$Al signatures as other melilite-hibonite-spinel CAIs and partially exchanged with the surrounding chondrule material when it was incorporated into the chondrule melt. The other objects may represent intermediate stages between these two extremes.

Except for the effects of terrestrial weathering on melilite, inclusions in Adelaide appear to retain the primary isotopic signatures acquired when they formed.  Adelaide is thus an ideal meteorite for investigating processes that produced chondrules and CAIs.

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